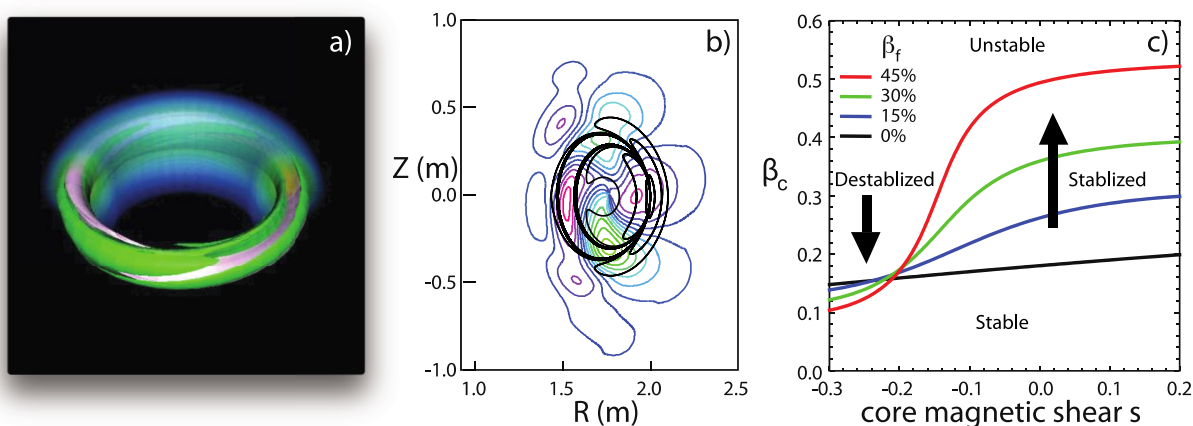


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Zero tolerance in tokamaks: eliminating small instabilities before they become disruptions

Disruptive resistive instabilities in tokamaks can be stabilized (or destabilized) by energetic ions from fusion reactions and beam heating, depending on the structure of the magnetic field in the device, theory and simulation analyses have shown.



A simulation a) of a disruptive instability in the DIII-D tokamak, a cross section b) showing orbits of trapped energetic ions (black) interacting with the magnetic instability (colors), and the dependence of the critical threshold c) in the ratio of thermal to magnetic energy, β_c , as a function of the magnetic shear (the normalized gradient of the field's helical pitch) in the core of the device. The critical threshold c) is from a theoretical model which explains the simulation results a), b), and experimental observations of the mode onset.

The Science

Simulations of tokamak discharges with fast, energetic ions have shown the emergence of a stabilizing influence to the disruptive “tearing” instability, which is considered the greatest challenge to sustaining fusion conditions as they generate imperfections in the magnetic field that confines the hot, ionized gas called a plasma. If left unchecked, these imperfections often result in a disruption, the sudden termination of the plasma discharge, both limiting the fusion production and threatening damage to the machine.

Whether the force is stabilizing or destabilizing depends on the “shear,” which measures how the magnetic field lines wrap around the donut-shaped, or toroidal, plasma. In positive shear, the usual case, the energetic ions are stabilizing. However, the inner region of tokamaks can often have low or negative (reversed) magnetic shear, and this leads to a destabilizing force, enough to drive the tearing mode unstable, thereby possibly leading to a disruption.

A recent theoretical analysis, by Dylan Brennan at PPPL and Michael Halfmoon at U. Tulsa has confirmed that tokamak discharges can be stabilized by energetic ions, under the right conditions.

The Impact

The onset of disruptions has long stood as a barrier to the realization of fusion energy in tokamaks by preventing access to the required high-confined-energy regimes. In large future tokamaks such as ITER, disruptions can also cause significant damage to the machine. Understanding the physics driving the *initial* onset of the *small-scale* instabilities that lead to large-scale disruptions allows experimentalists to avoid the disruptions by suppressing the instabilities before they can grow. This “zero tolerance” approach allows better control of the plasma, and this is of utmost importance in the development of stable operational scenarios.

Advanced tokamaks achieve high-thermal-energy plasmas by injecting beams of hot ions that collide with, and thereby heat, the background plasma. Burning plasma experiments that create energy from fusion reactions, such as ITER, will also have a significant population of hot alpha particles, the by-product of fusion.

The effects that energetic ions have on the benign instabilities, such as the so-called sawtooth instability, which causes the temperature near the plasma core to flatten, and the so-called toroidal Alfvén eigenmode, which intuitively is a “vibration” (wobble) of the magnetic fieldlines, has been known for some time. The unique finding in this work is that the energetic ions have been found to also be a potent driver to the instabilities that cause disruptions. Energetic ions, ubiquitously present in fusion plasmas, can be a strong stabilizing or destabilizing force, depending on the magnetic shear in the plasma. As we move toward controlled avoidance of disruptions in ITER, effects like these will be critical to take into account.

Summary

As the current and confined energy in plasmas are increased, a “stability boundary” can be crossed when the thermal pressure (i.e., the heat energy) exceeds a certain fraction of the magnetic energy that comprises the magnetic bottle that confines the plasma. These “tearing” instabilities create imperfections in the magnetic field, like small, isolated eddies in a stream of water. If these imperfections grow they can trigger a large-scale disruption, which terminates the plasma confinement and can damage the machine.

These energetic ion populations interact with a variety of usually benign instabilities, such as the sawtooth instability and the toroidal Alfvén eigenmode. This work has now shown that the energetic ions can strongly drive the dangerous tearing instabilities. Understanding the physics driving the initial onset of the observed instabilities can lead to their avoidance, and is of utmost importance in the development of stable operational scenarios. These results also explain many experimental observations of how, and when, the tearing instabilities limit the maximum thermal pressure that the magnetic fields in tokamaks can support.

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